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NUMERICAL CALCULATION OF INTERNAL TURBULENT FLOW CHARACTERISTICS INSIDE A PUMP AS TURBINE

He-Chao Guo*, Shen Chen, Fu-Yi Zhang, Zhi-Yang Zhao, Ke-Xin Xie, Qi-Kai Gong

College of Mechanical Engineering, Quzhou University, Quzhou, 324000, China.

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***Corresponding Author**
He-Chao Guo
College of Mechanical Engineering, Quzhou University, Quzhou, 324000, China.
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ABSTRACT

To address the issue of unclear internal turbulent flow characteristics when a centrifugal pump operates in reverse as a hydraulic turbine, the standard RNG k-ε turbulence model was adopted, with liquid water as the working medium. Numerical calculations were performed on the internal flow of this hydraulic turbine, and the turbulent flow characteristics of the fluid inside the turbine were analyzed. The results indicate that: the overall turbulent kinetic energy level of the volute is low, which increases slightly with the rise of inlet flow rate, and flow disturbances in the region adjacent to the impeller contact surface are weak; the turbulent kinetic energy at the volute tongue is significantly higher than that in other regions of the volute—it is uniformly distributed under low operating conditions, while under high operating conditions, it exhibits intense fluctuations and high concentration, with prominent vortex phenomena; for the impeller, the turbulent kinetic energy decreases monotonically along the flow channel under low operating conditions; under high operating conditions, the fluid disturbance at the outlet increases sharply, and the distribution of turbulent kinetic energy deviates from a steady state; the turbulent kinetic energy in the middle region of the outlet section is relatively high, which tends to result in a decrease in flow stability.

KEYWORDS: Pump as Turbine, Centrifugal Pump, Turbulent Kinetic Energy, Entropy Production.

1. INTRODUCTION

As an efficient energy recovery device, the Pump as Turbine (PAT) is widely applied in industrial sectors such as petrochemical hydrogenation systems, coal chemical gas purification processes, and high-pressure water recovery in seawater desalination, thanks to its advantages of compact structure and low cost. In practical operation, PAT's operating conditions often fluctuate with the load of industrial processes. Under low, medium, and high flow rate conditions, its internal flow field is prone to turbulence-induced issues like flow separation, vortexes, and pressure pulsations—these problems not only intensify energy dissipation but also reduce operational stability. Consequently, in-depth investigation into the internal turbulent flow characteristics of PAT under multiple operating conditions has become crucial for enhancing its energy conversion efficiency and operational reliability.

Domestic research on the variable-condition flow of PAT and centrifugal pumps has achieved certain progress. Wang Yang et al.[1] compared the performance of low-specific-speed centrifugal pumps with and without splitter blades via numerical simulation; using the standard k-ε turbulence model, they captured the scouring effect of splitter blades on the wake, which effectively suppressed liquid separation, though their study did not involve performance correlation laws under turbine reverse rotation. Xia Zhengting et al.[2] established a performance conversion and correction model for low-specific-speed pumps operating in reverse as turbines, and numerical calculations at 12 operating points verified the model error to be less than 6%, clarifying the role of flow channel structure optimization in improving turbine efficiency—yet the study lacked in-depth analysis of the spatial distribution characteristics of internal turbulence. Lu Hongzhong et al.[3] measured the absolute velocity distribution in the impeller of a low-specific-speed centrifugal pump using Particle Image Velocimetry (PIV) technology, with the deviation between experimental data and numerical simulation controlled within 5%, providing reliable experimental support for flow field analysis; however, their research only covered the forward operating condition of centrifugal pumps. Wang Tao et al.[4] analyzed the impact of blade inlet installation angle on PAT's external characteristics, finding that a 15°~20° angle could increase turbine efficiency by 3%~5%, but failed to explore the regulatory effect of blade angle on turbulence intensity in regions like the volute and volute tongue. Dai Cui et al.[5] obtained the relative velocity distribution in the full flow channel of a centrifugal pump impeller by combining unsteady numerical calculation and PIV experiments, verifying the turbulence model's accuracy in capturing vortex structures, yet their research did not extend to PAT's multi-condition scenarios, offering no reference for variable-load operation. He Youshi et al.[6] conducted variable-condition numerical analysis on the impeller of a centrifugal pump with splitter blades, discovering that splitter blades could suppress backflow under small flow conditions, but did not study the turbulent characteristics of PAT's volute tongue region. Li Yibin et al.[7] performed full-flow-channel numerical simulation on a low-specific-speed stamping-welded centrifugal pump using the RNG k-ε model, finding that adding splitter blades reduced secondary flow loss at the impeller outlet by 12%~15%—their turbulence loss correction method provided a reference for turbine optimization under high conditions, but did not involve entropy production characteristics during reverse rotation. Huang Ning et al.[8] analyzed hydraulic turbine energy loss under different conditions based on entropy production theory, pointing out that runner entropy production accounts for 44% under design conditions, while vortex-induced turbulence pulsations increase the entropy production rate by over 30% under off-design conditions.

Currently, research on the full flow channel of low-specific-speed PAT—integrating turbulent kinetic energy and entropy production for joint analysis under multiple operating conditions—remains insufficient, failing to fully reveal the intrinsic mechanism of turbulence-induced energy dissipation under different conditions. Taking a low-specific-speed centrifugal pump operating in reverse as a turbine as the research object, this study adopts the standard RNG k-ε turbulence model and uses liquid water as the working medium to conduct numerical calculations on the full flow channel under three operating conditions (low, medium, and high). The research results are expected to provide theoretical support for the multi-condition optimization design of low-specific-speed PAT, the suppression of abnormal flow, and the extension of its service life.

2. COMPUTATIONAL MODELS AND METHODS

2.1 Computational Model

The prototype pump of the centrifugal pump operating in reverse as a hydraulic turbine is a low-specific-speed centrifugal pump, with the following design parameters: flow rate of 20 m^3/h, head of 34 m, and rotational speed of 2900 r/min. For detailed structural parameters, see Table 1.

Tab. 1: Main structural parameters.

Main Structure	Parameter	Value
Impeller	Inlet Diameter D_1/mm	124
	Outlet Diameter D_2/mm	44
	Inlet Width b_1/mm	10
	Blade Wrap Angle /(°)	135
Volute	Inlet Diameter D_s/mm	32
	Outlet Width b_0/mm	16
	Base Circle Diameter D_0/mm	140
Inlet Section	Diameter D_{in}/mm	32
	Length L_{in}/mm	100
Outlet Section	Diameter D_{out}/mm	44
	Length L_{out}/mm	55.5

2.2 Computational Method

The overall computational domain mesh is shown in Fig. 1, and the number of meshes in each region is listed in Tab. 2. For the internal flow calculation, the RNG k-ε turbulence model was selected[9], with liquid water used as the working medium. Meanwhile, the turbine inlet was set as a velocity inlet boundary condition, and the outlet was set as a free pressure outlet boundary.

Fig. 1: Overall Model Mesh.

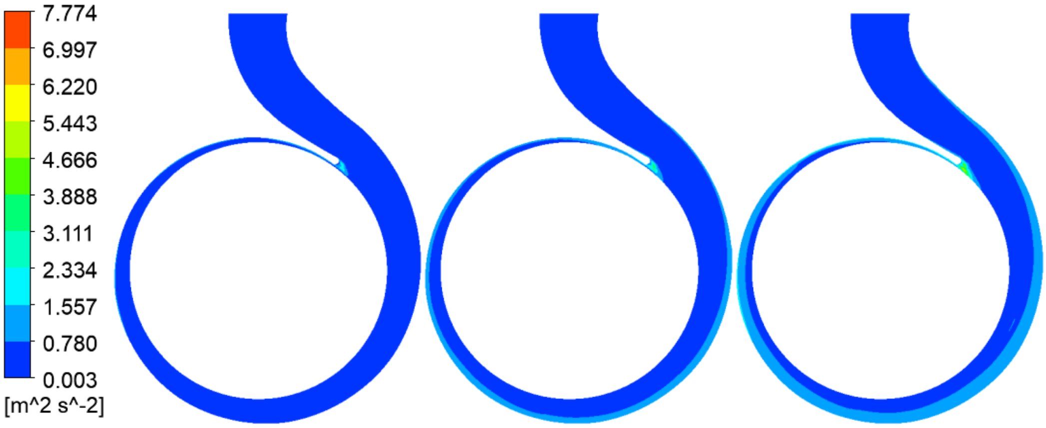
Tab. 2: Mesh Count.

Region	Inlet Section	Volute	Impeller	Outlet Section
Mesh Count	25200	472946	1239259	162048

3. RESULT ANALYSIS

3.1 Volute Turbulent Kinetic Energy

By analyzing the contour maps of turbulent kinetic energy, the distribution characteristics of internal flow energy in the volute of the centrifugal pump-turbine under different operating conditions can be directly observed, which assists in evaluating the flow stability. The results of the changes in the contour maps of turbulent kinetic energy distribution in the centrifugal pump-turbine volute with operating conditions are shown in Fig. 2.



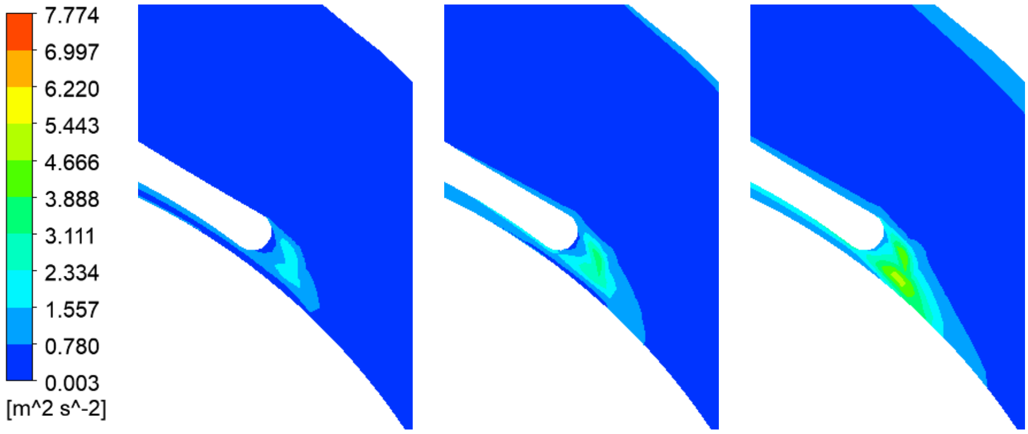
(a) Low Operating Condition **(b) Middle Operating Condition** **(c) High Operating Condition**

Fig. 2 Distribution of Turbulent Kinetic Energy in Volute of Centrifugal Pump-Turbine.

An investigation was conducted on the distribution of turbulent kinetic energy in the volute of the centrifugal pump-turbine under low, medium, and high operating conditions. The results indicate that the turbulent kinetic energy in the volute is generally low, and the fluid flow in this region exhibits low-disturbance characteristics. With improved operating conditions and increased inlet flow rate, the turbulence intensity on the volute surface increases slightly; the increase in flow velocity and turbulence intensity may be the contributing factors. In the region adjacent to the impeller contact surface, the flow disturbance is weak, and the fluid flow disturbance in the near-wall region of the impeller is small, which may have a positive effect on improving pump efficiency.

3.2 Volute Tongue Turbulent Kinetic Energy

Analysis of the fluid motion characteristics in the volute tongue region of the centrifugal pump-turbine can be realized by visualizing the distribution of turbulent kinetic energy through multi-condition contour maps. Meanwhile, Fig. 3 presents a comparison of the turbulent kinetic energy distribution under different operating conditions for this region.



(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

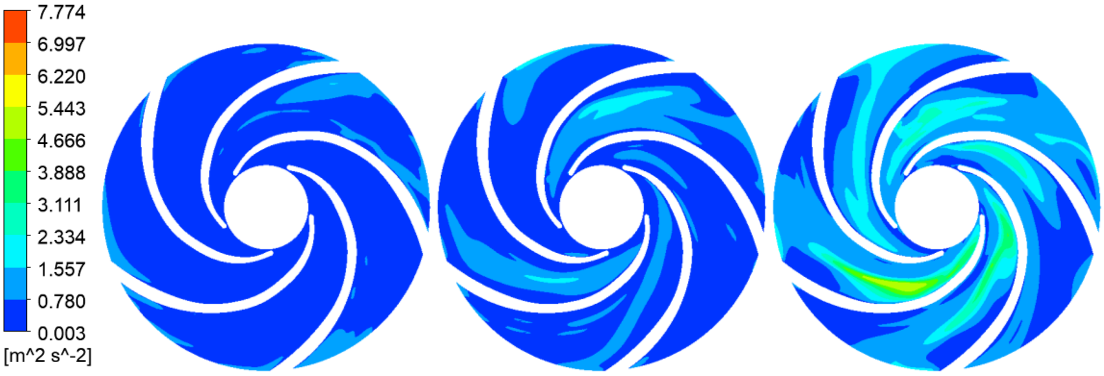
Fig. 3 Distribution of Turbulent Kinetic Energy in Volute Tongue of Centrifugal Pump-Turbine.

Under three typical operating conditions (low, medium, and high), the turbulent kinetic energy distribution in the volute tongue part of the centrifugal pump-turbine exhibits significant differences. Compared with other regions of the volute, the turbulent kinetic energy values at the volute tongue are generally higher. Under low operating conditions, the turbulent kinetic energy distribution in the volute tongue region is relatively uniform, indicating a relatively stable flow state; as the operating condition increases to the medium level, the turbulent kinetic energy values begin to increase significantly, and the emergence of local high-value areas implies the initial formation of vortices; under high operating conditions, the turbulent kinetic energy in the volute tongue region shows a trend of intense fluctuation and high concentration, with turbulence activity significantly enhanced. As the inflow medium flow rate continues to increase, the rise in flow velocity further intensifies the turbulence, resulting in an increasingly complex flow field structure.

3.3 Impeller Turbulent Kinetic Energy

The contour maps of turbulent kinetic energy for the impeller of the centrifugal pump-turbine under different operating conditions are shown in Fig. 4. By conducting a comparative analysis of the turbulent kinetic energy distribution in the impeller of the centrifugal pump operating as a turbine under low, medium, and high operating conditions, several core laws can be summarized: under low-performance operating conditions, the fluid turbulent kinetic energy decreases monotonically from the inlet to the outlet of the impeller, indicating stable fluid motion and a low turbulence level; under high-load operating conditions, the turbulent kinetic energy around the impeller increases sharply, and the energy of the fluid at the outlet fluctuates significantly, causing the turbulent kinetic energy distribution to deviate from the steady state.

As the operating state intensifies (i.e., the inlet flow rate increases), the turbulent kinetic energy of the impeller increases simultaneously. During the low operating condition phase, the turbulent kinetic energy in the impeller region reaches its minimum value, which indicates good flow stability under this state. In the high-load phase of the system, with the increase in the impeller load, the turbulent kinetic energy rises sharply, reflecting more intense flow disturbances. Although the increased turbulent kinetic energy is conducive to fluid mixing, it will reduce the efficiency accordingly.

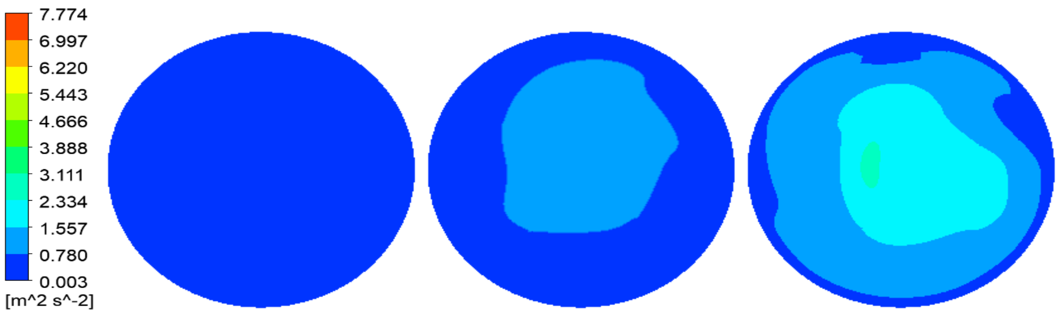


(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 4: Contour Map of Turbulent Kinetic Energy in Impeller of Centrifugal Pump-Turbine.

3.4 Turbine Outlet Section Turbulent Kinetic Energy

The contour maps of turbulent kinetic energy of the fluid in the outlet section of the centrifugal pump-turbine under different operating conditions can reflect the regions with high flow velocity or abrupt changes in flow. The distribution of turbulent kinetic energy in the outlet section of the centrifugal pump-turbine under different operating conditions is shown in Fig. 5.



(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 5: Distribution of Turbulent Kinetic Energy in Outlet Section of Centrifugal Pump-Turbine.

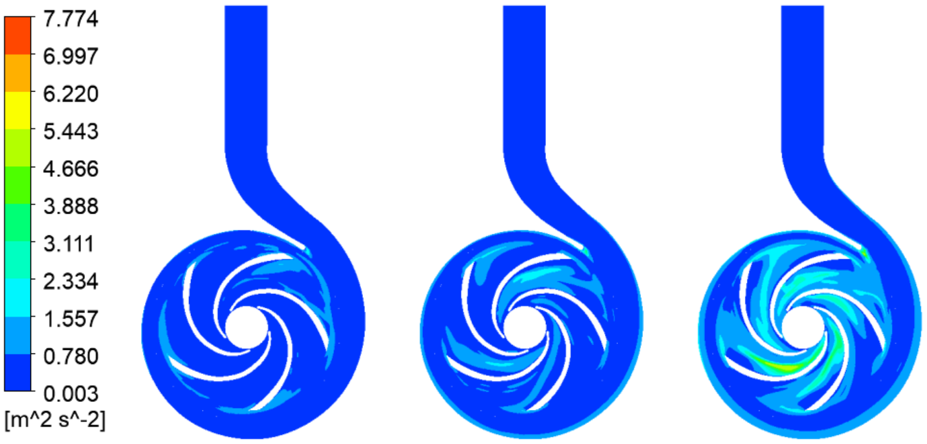
An analysis of the contour maps of turbulent kinetic energy in the outlet section of the centrifugal pump-turbine under low, medium, and high operating conditions was conducted, and it is found that the turbulent kinetic energy level near the outlet of the outlet section is low, while the overall turbulent kinetic energy level is also low. However, the turbulent kinetic energy in the central region of the outlet section is significantly higher—fluid motion in this region is intense with significant disturbances, which tends to reduce flow stability and system efficiency.

With changes in operating conditions, the inflow rate increases, leading to a significant growth in the turbulent kinetic energy of the outlet section. Under high-energy operating conditions, the flow in the central region of the outlet section becomes complex, characterized by a notable increase in turbulent kinetic energy.

3.5 Overall Turbulent Kinetic Energy

A comparison of the turbulent kinetic energy under different operating conditions in the overall flow field of the centrifugal pump operating as a turbine is shown in detail in Fig. 6. A study was conducted on the overall distribution of turbulent kinetic energy in the centrifugal pump-turbine under low, medium, and high operating conditions, revealing that the turbulent kinetic energy in all regions is generally low. However, in the impeller section near the turbine outlet, the turbulent kinetic energy increases sharply; the dynamic disturbance of the fluid near the impeller intensifies, and the flow state exhibits complexity. The turbulent kinetic energy is the lowest in the section from the centrifugal pump outlet to the turbine inlet. As water flows through the volute into the impeller, the turbulence effect gradually intensifies.

As the operating intensity increases (i.e., the medium flow rate grows), the turbulent kinetic energy of the centrifugal turbine shows an upward trend. The efficiency of energy transfer and mixing of the fluid in the pump chamber significantly improves, with the most notable change observed in the spatial distribution of turbulent kinetic energy.

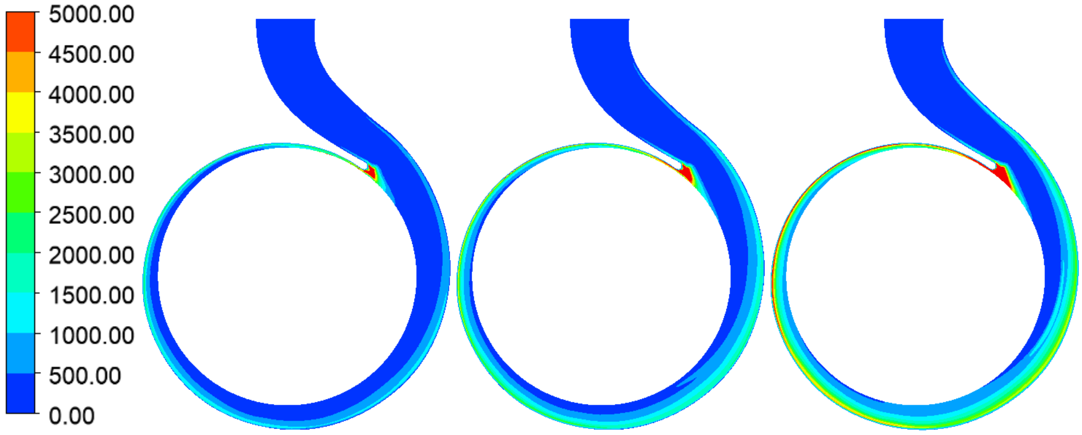


(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 6: Overall Contour Map of Turbulent Kinetic Energy of Centrifugal Pump-Turbine.

3.6 Entropy Production Distribution

Under the condition of constant rotational speed, the differences between centrifugal pump and turbine operating conditions were analyzed. The volute entropy production[10] contour maps can present the specific spatial locations and relative intensities of flow losses; meanwhile, the entropy change contour maps enable the identification of dissipation-concentrated regions, the evaluation of energy consumption levels under various operating conditions, and further reveal the energy consumption characteristics of the internal flow in the volute. The entropy production contour maps can reflect the differences in energy conversion mechanisms under different operating conditions. When the turbine function is adopted, entropy production is mainly distributed in the diffuser section and around the outlet; the phenomenon of increased entropy production in the volute spiral section and at the volute tongue is particularly prominent, and this phenomenon is related to flow direction characteristics, pressure gradient evolution, and inertial effects. Fig. 7 presents the distribution of entropy production in the volute of the centrifugal pump-turbine under multiple operating conditions.

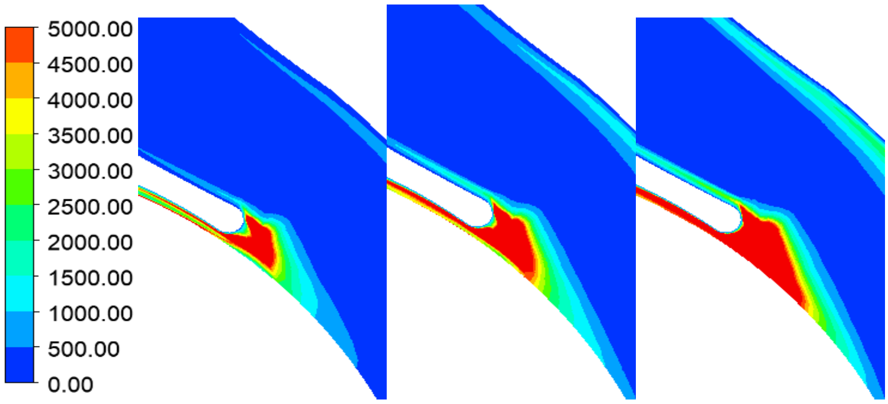


(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 7: Contour Map of Entropy Production in Volute of Centrifugal Pump-Turbine.

Comparative analysis shows that under low, medium, and high operating conditions, the distribution of entropy production in the volute exhibits the following characteristics: in regions far from the interface with the impeller, entropy production increases significantly, and irreversible losses are relatively prominent; in regions near the impeller interface, the entropy production rate decreases noticeably, and irreversibility is significantly reduced. As the operating conditions improve and the inflow rate increases, the overall entropy production value gradually rises, the energy loss rate increases significantly, and the entropy production level in the peripheral region of the impeller increases markedly—leading to a notable expansion of the high-entropy-production range. During the operation of the turbine equipment, there is an obvious flow velocity gradient in the diffuser section of the volute outlet and its far side; energy losses caused by flow separation and turbulent dissipation occur more frequently, and such irreversible losses will expand as the flow rate increases.

The study on the contour maps of entropy production in the volute tongue of the centrifugal pump-turbine under constant rotational speed and different operating conditions is mainly aimed at systematically presenting the spatiotemporal distribution law of energy dissipation. The entropy production contour maps are displayed through changes in color gradients or contour lines, reflecting the spatial distribution differences in the intensity of energy dissipation in the volute tongue region with varying operating conditions. It can be observed from the entropy production contour maps that during the low-output operating condition phase, local concentration of entropy production may exist in the volute tongue region—indicating a slight blockage in the flow path. As the operating conditions improve, the number of high-entropy-production zones in the volute tongue region increases and their range gradually expands, which indicates a further intensification of energy dissipation. There is a direct correlation between the operating parameters of the centrifugal pump-turbine and such energy losses. Fig. 8 presents the distribution law of the entropy production contour maps of the centrifugal pump-turbine volute tongue with changes in operating conditions.



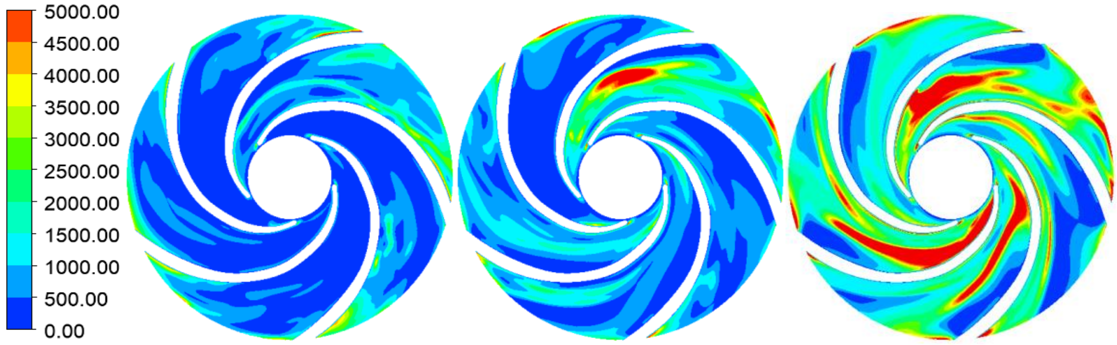
(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 8: Contour Map of Entropy Production in Volute Tongue of Centrifugal Pump-Turbine.

By comparing the entropy production contour maps of the volute tongue region under three operating conditions of the centrifugal pump operating in reverse as a turbine, the flow dissipation characteristics of this key component can be clearly identified. There exist significant gradient differences in entropy production near the volute tongue: the greater the entropy generation near the volute tongue tip, the more significant the energy conversion loss at this location. This loss is mainly caused by flow separation, impact, and intense turbulent dissipation that occur when the fluid flows past the volute tongue.

As the load conditions change from low to high, the flow state at this component changes significantly, and the overall entropy production level increases sharply. At the rated rotational speed, the peak entropy production under high operating conditions is significantly higher than that under low operating conditions, and the spatial proportion of the peak entropy production region increases remarkably. Obvious concentration zones appear near the flow-facing surface of the volute tongue, and the form of energy loss shifts: under low operating conditions, the loss caused by flow separation dominates, while under high operating conditions, it is the joint effect of impact loss and turbulent dissipation.

Through the visualization method of entropy production contour maps, the evolution of energy dissipation in the impeller of the centrifugal pump-turbine under constant rotational speed and different operating conditions can be clearly displayed, and the main energy dissipation zones can be quickly identified—thereby effectively distinguishing complex phenomena such as flow separation inside the impeller. Studying the relationship between operating parameters and the energy conversion effect of the impeller serves as a key basis for the optimal design of blade configurations (e.g., shape, angle, quantity), which helps reduce energy loss and optimize impeller performance. Based on the distribution distortion characteristics of entropy production contour maps, potential abrasion or deposition defects on the impeller's working surface can be timely detected, ensuring the long-term stable and efficient operation of the centrifugal pump-turbine. Differences in the distribution of entropy production contour maps of the centrifugal pump-turbine impeller under different operating conditions can be observed in Fig. 9.



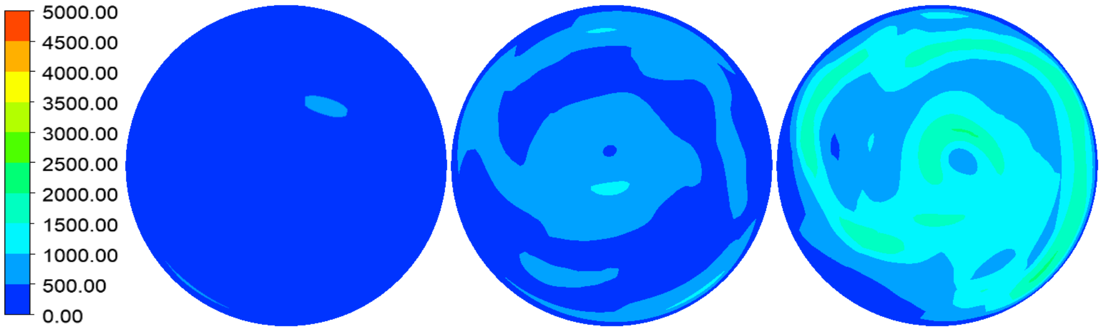
(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 9: Contour Map of Entropy Production in Impeller of Centrifugal Pump-Turbine.

A systematic analysis was conducted on the entropy production contour maps of the impeller region of the centrifugal pump-turbine under low, medium, and high load conditions, which revealed the spatial distribution law and variation trend of flow losses within the impeller region. The calculation results indicate that during the low rotational speed operation stage, the entropy production phenomenon in the impeller inlet section (turbine outlet side) is not severe, suggesting that the flow development at this cross-section proceeds relatively smoothly.

As the flow proceeds, there exists a significant high-entropy-production zone near the trailing edge and at the junction with the flow channel. This is due to the prominent flow separation and secondary vortex evolution during low-speed operation. With the increase in operating condition levels, the energy loss mechanism of the impeller undergoes a significant change: in the leading edge region, the direct impact of high-velocity fluid on the blade leading edge causes impact loss, leading to significant entropy production accumulation; the area of the high-entropy region on the pressure side of the trailing edge increases by a factor of 2 to 3; turbulent dissipation rises during the formation of the tip clearance vortex system; and the entropy production intensity in the middle channel of the blade and the trailing edge region increases significantly, forming a high-dissipation core that penetrates the flow channel.

By adopting the method of entropy production comparison under multiple operating conditions, the energy dissipation status of the centrifugal pump-turbine outlet section at a constant rotational speed was accurately evaluated, the entropy production accumulation trend was intuitively reflected, and the high-entropy-production sections were identified—thus analyzing the influence of operating parameters on the flow pattern distribution of the outlet section. Comparing the entropy production parameters under different operating conditions enables an understanding of the energy conversion capacity of the outlet section under varying operating conditions, which is conducive to the improvement of the outlet section structure and the enhancement of overall efficiency. Monitoring abnormal entropy production can timely detect potential blockage and wear issues in the outlet section, ensuring the long-term reliable operation of the centrifugal pump-turbine. The distribution results of the entropy production contour maps of the outlet section under different operating conditions are shown in Fig. 10.

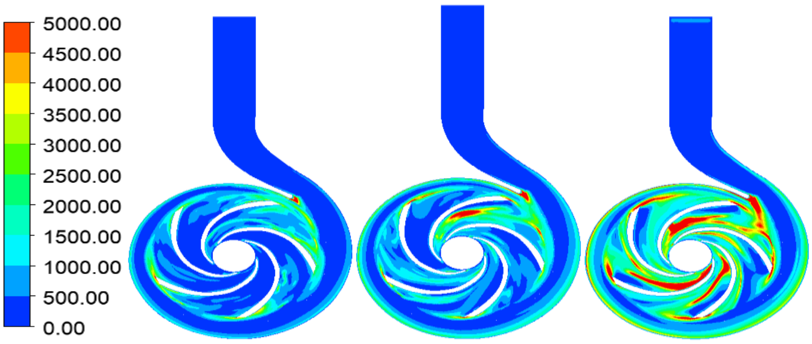


(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 10 Contour Map of Entropy Production in Outlet Section of Centrifugal Pump-Turbine.

A comparative study was conducted on the entropy production contour maps of the outlet section of the centrifugal pump-turbine under low, medium, and high operating conditions. It was found that distinct core entropy production zones and peripheral low-value zones are formed at the outlet cross-section. This is attributed to the high flow velocity and intense turbulent fluctuations in the central region; under the effect of the wall boundary layer, the local flow velocity decreases. During operation according to the design parameters, the spatial distribution of entropy production is relatively uniform, while there are obvious extreme values in the outlet section along the central line. The backflow phenomenon will disperse the distribution of entropy production.

The entropy production characteristics of the centrifugal pump-turbine under variable operating conditions at the same rotational speed are reflected through color contour maps and contour lines, which can intuitively display the spatial distribution patterns of energy consumption under various load conditions. This method enables the effective identification of high-entropy-production concentrated regions and the determination of the aggregation range of energy losses, as well as the systematic analysis of the spatial gradients and magnitudes of energy dissipation of the equipment under variable load conditions. From the perspective of performance improvement, based on the energy consumption distribution laws obtained from contour map analysis, the geometric characteristics of components such as the impeller and volute can be accurately adjusted, the flow channel geometry can be optimized, and the impacts of adverse flows (e.g., boundary layer separation and vortices) can be mitigated. This reduces the amount of system entropy generation and improves the energy conversion efficiency and operating performance of the centrifugal pump-turbine. The overall contour map distribution characteristics of entropy production in the centrifugal pump-turbine under different operating conditions are shown in Fig. 11.



(a) Low Operating Condition (b) Middle Operating Condition (c) High Operating Condition

Fig. 11 Overall Contour Map of Entropy Production of Centrifugal Pump-Turbine.

An analysis was conducted on the overall entropy production contour maps of the centrifugal pump-turbine under low, medium, and high operating conditions. It can be observed that in the overlapping region of the turbine inlet and the pump discharge section, the entropy production in this fluid domain remains relatively low with minimal energy dissipation—this is due to the uniform velocity distribution of the fluid in the initial flow stage. When the working fluid flows along the inner cavity of the volute, there is no significant change in entropy production around the impeller, which is attributed to the reasonable flow direction control structure installed here.

At the initial stage when the fluid flows through the impeller flow channel, the difference in entropy production distribution is significant, with distinct entropy production enhancement zones appearing on both side walls of the impeller. As the operating conditions improve, the entropy production value in the impeller section near the outlet increases rapidly, leading to significant energy loss in this region. The peak entropy production at the end of the suction surface is 3 to 4 times higher than that at the inlet section, which is mainly caused by boundary layer separation and wake dissipation.

4. CONCLUSION

The overall turbulent kinetic energy level of the volute is relatively low, increasing slightly with the increase in inlet flow rate, and the flow disturbance in the region adjacent to the impeller contact surface is weak, which is conducive to improving operating efficiency; the turbulent kinetic energy of the volute tongue is significantly higher than that in other regions of the volute—it distributes uniformly under low operating conditions, increases in value and intensifies in fluctuation under medium and high operating conditions, and forms local high-value zones accompanied by strong vortices under high operating conditions; for the impeller, the turbulent kinetic energy decreases monotonically along the flow channel and the flow is stable under low operating conditions, while under high operating conditions, the fluid disturbance at the outlet increases sharply and the turbulent kinetic energy distribution deviates from the steady state; the turbulent kinetic energy in the central region of the outlet section is relatively high, which easily leads to a decrease in flow stability. Meanwhile, entropy production shows a significant increasing trend with the improvement of operating conditions, and the volute diffuser section, volute tongue, and impeller trailing edge are concentrated areas of energy dissipation: under low operating conditions, energy loss is dominated by flow separation, while under high operating conditions, it is jointly dominated by impact loss and turbulent dissipation; additionally, the peak entropy production at the end of the impeller suction surface is 3 to 4 times higher than that at the inlet section.

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